Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 142 (2017) 1991–1996

Energy Procedia

www.elsevier.com/locate/procedia

• 9th International Conference on Applied Energy, ICAE2017, 21-24 August 2017, Cardiff, UK

Performance and Benefits of Distributed Energy Systems in Cooling Dominated Regions: A Case Study

Jing Kang[a], Shengwei Wang[a,*], Wenjie Gang[a,b]

[a]*Department of Building Services Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong*
[b]*Department of Building Environment and Energy Engineering, Huazhong University of Science and Technology, Wuhan, China*

Abstract

The distributed energy system (DES) is an innovative energy system with high energy efficiency and economic benefits. However, the application of this energy system in cooling dominated regions is still not well studied yet. This paper aims to investigate the performance and benefits of the DES in Hong Kong. Based on the characteristic of energy demands, a DES, which integrates distributed generations and district cooling systems, is designed. The chilled water distribution networks and the pumps systems are determined by the cooling demand. An optimal design approach is adopted in equipment sizing of the DES. Based on the modeling results, the hourly energy consumptions of the DES and the CES (centralized energy system) are compared. In the DES, the grid load is reduced significantly, and the cooling system operates with a higher efficiency during the most period of the year. The primary energy saving and the cost saving of the DES are analyzed and discussed. Results denote that the DES can achieve a primary energy saving of 9.58%. Even the capital cost becomes higher, the DES is also economically beneficial due to the low operation cost.

Keywords: Distributed energy system; cooling dominated regions; district cooling system, high efficiency, energy saving; economic benefits

1. Introduction

The centralized energy systems (CESs) will have problems when meeting the challenges brought by the building energy consumption increase and the requirement of CO_2 emissions reduction. To satisfy the reliability of energy supply, renewal of power plants and the grid, which costs lot, ought to be implemented in CESs [1]. International society and governments have been paying great attention and making much effort to find alternatives to conventional

---

* Corresponding author. Tel.: +852 2766 5858; fax: +852 27746146
E-mail address: beswwang@polyu.edu.hk

10.1016/j.egypro.2017.12.400

energy supply schemes for the purpose of improving energy efficiency and reducing operation cost. Distributed energy systems (DESs), an innovative energy supply system serving a district, have attracted great attention recently due to low carbon emissions, high energy efficiency and reliability. In the DES, distributed generations (DGs), like gas engines/turbines and renewable energy sources (solar penal/wind turbine), supply electrical energy. District heating or cooling systems (DHSs/DCSs) satisfy the demand of thermal energy [2].

For the application of DESs, many studies focus on the DESs for regions where only heating, or both space heating and cooling are needed [3]. By using the existing heating distribution networks, the capital cost of DESs which integrated with DHSs can be reduced. The pumps consumption and the heat loss are important issues in thermal energy delivery. DHSs is more suitable in long distance delivery than DCSs due to the lower heat loss. Thus, the application and the performance of DESs which integrated with DCSs, are rarely investigated yet. However, with the development of DCSs, a lot of cases and studies proved that this system has benefits compared with individual cooling systems (ICSs), in cooling dominated regions which requires space cooling annually [4].

Hong Kong is a typical city in cooling dominated region with high density energy demands. For the future development, the government has set it policy to develop DCSs for cooling supply and replace coal gradually by natural gas as primary energy in power generation [5]. It is worthwhile to investigate the beneficial energy supply scheme under this situation. This paper investigates the performance of a district integrated DES (DGs and DCSs) in a Hong Kong campus. Though comparing with the corresponding CES (centralized power plant and ICSs), the benefits of the DES are highlighted. Three important issues on the application of the DES are studied and discussed:

- The impacts of the DES on the utility grid, for example, the load shaving
- The efficiency of cooling supply systems/equipment
- The overall energy saving and economic benefits of the DES

2. Configuration of the district integrated DES

The DES consists of three mainly components: 1) energy supply equipment, which supply electricity and cooling; 2) energy distribution networks, which transfers and dispatches the energy; 3) end users. Three categories of equipment, distributed generations (DGs) for electricity generating, absorption chillers (ACs) and electric chillers (ECs) for cooling producing, are adopted as energy suppliers in this study. Fig. 1 shows the basic layout of DES. All equipment locates in a central energy station. The electricity from the utility grid and DGs is uploaded into the microgrid. The chilled water (CHW) produced by chillers is delivered to end users through chilled water networks. To overcome the resistance of the network, a pumps system is adopted to provide enough deliver pressure.

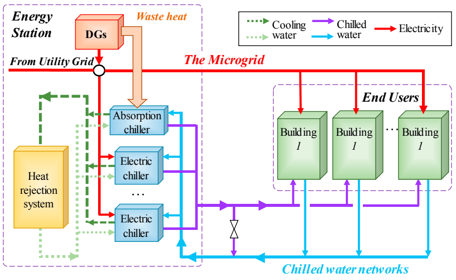

Figure 1. The layout of DESs integrated with DCSs

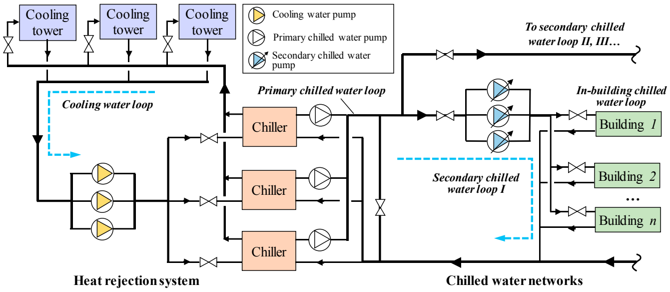

Figure 2. Schematic of the cooling system

Structure and cost of CHW networks are important in DCSs design. In this study, as shown in Fig. 2, the networks consist of three CHW loops: the primary loop, the secondary loops and in-building loops. The primary loop is the closed CHW loop which connects chillers inside the energy station. Constant speed pumps are adopted as primary pumps to supply sufficient head for chillers in this loop. The secondary loops transfer the CHW from the energy station to users. A group of various speed secondary pumps, which can adjust the speed of pumps according to the CHW flow rate, are adopted in each secondary loop. The in-building loop is the closed CHW loop inside each building. In this study, in-building loops connect secondary loops directly.

3. Optimal design

3.1. Objective function

A cost-optimal design method is adopted to determine the capacity of DES. The system payback period (PBP), which indicates how long the additional capital cost can be recovered if the DES replaces the CES, equals to the ratio of the additional capital costs and the annual operating costs saving. The objective function, which should be minimized, is defined as Eq. 1. Where Cc_{eq} is the capital cost of equipment. CP is the equipment capacity. n_1 and n_2 are the number of equipment in the DES and the CES. The operation cost of the CES, as Eq. 2 shows, includes the total electricity demand and the power consumption of electric chillers in each building. The operation cost of the DES, as Eq. 3 shows, equals to the sum of system energy cost and the maintenance cost, subtracted by the energy saving incentive. Where $Cost_e$ and $Cost_f$ are prices of electricity and natural gas. $Cost_{e,sell}$ is the feed-in tariff. CM_{DG} is the maintenance cost coefficient. PS is the incentive coefficient of energy saving. F_{DES} is the primary energy consumption of DES and F_{CES} is the consumption of CES.

$$\min PBP = \frac{\Delta Cc}{\Delta Oc} = \frac{Cc^{DES} - Cc^{CES}}{Oc^{CES} - Oc^{DES}} = \frac{\sum_{m=1}^{n_1} CP_m \cdot Cc_{m,eq} - \sum_{n=1}^{n_2} CP_n \cdot Cc_{n,eq}}{Oc^{CES} - Oc^{DES}} \tag{1}$$

$$Oc^{CES} = \sum_{i=1}^{365}\sum_{k=1}^{24}\left(E_{ik,d} + \sum_{j=1}^{n} \frac{C_{ik,j}}{COP_{ik,j}} \right) \cdot Cost_e \tag{2}$$

$$Oc^{DES} = \sum_{i=1}^{365}\sum_{k=1}^{24}\left[(E_{ik,grid} \cdot Cost_e + F_{ik,DG} \cdot Cost_f - E_{ik,sell} \cdot Cost_{e,sell}) + CM_{DG} \cdot E_{ik,DG} - \left(F_{ik}^{CES} - F_{ik}^{DES} \right) \cdot PS \right] \tag{3}$$

3.2. Equipment and control constraint

Two gas engine distributed generations (DGs) are adopted to generate electricity for the whole campus. According to the production manual [6], the total heat efficiency ($\eta_{T,FL}$) and the practical efficiency (η_{DG}) can be estimated as Eqs. 4 and 5. Where r_p is the part load ratio. The primary energy consumption of DGs (F_{DG}) equals to the generated electricity (E_{DG}) divided by the practical efficiency.

$$\eta_{T,FL} = 0.023\ln(CP_{DG}) + 0.703 \tag{4}$$

$$\eta_{DG} = (1.334r_p^3 - 3.208r_p^2 + 2.605r_p + 0.268)\left[0.042\ln\left(CP_{DG}\right) + 0.115\right] \tag{5}$$

The practical COP of an electric chiller is calculated based on the model in Ref. [7, 8]. The power consumption of electric chillers equals to the cooling load divided by the practical COP. Absorption chillers are assumed to be able to utilize the overall waste heat from DGs. Thus, the outputs of absorption chillers, as Eq. 6 shows, is the product of the recovered waste heat and chillers COP, which is assumed to be a fixed value as 1.20.

$$C_{ac} = F_{DG}(\eta_{T,FL} - \eta_{DG}) \times COP_{ac} \tag{6}$$

The electricity consumption of CHW pumps consists of the primary pumps consumption and secondary pumps consumption of each loop as shown in Eq. 7. Where H and Q are the pump head and flow volume. The flowrate of secondary loop is that required to maintain the constant supply and return temperature differential. N_{PP} is the number of operating primary pump. In the DES, the overall electricity demand is the sum of in-building power demands, the consumption of chillers, heat rejection system and CHW pumps. The energy output, both electricity and cooling, cannot exceed the capacities of equipment. The control strategy decides the operating of equipment in the DES for a period dt, i.e., one hour in this study. For each hour, the DES must operate to saving the maximum primary energy consumption compared with the CES. Thus, the operating of DES should satisfy the function as Eq. 8. The efficiency of central power plants, η_{grid}, is fixed to be 50%.

$$E_{pump} = (N_{PP} H_{PP} Q_{PP} g / 3600\eta) + \sum_{i=1}^{n} (H_{i,SP} Q_{i,SP} g / 3600\eta) \tag{7}$$

$$\max \int \frac{(F_{CES} - F_{DES})}{F_{CES}} dt = \int \frac{\frac{1}{\eta_{grid}} \cdot (E_{d,CES} + E_{sell,DES}) - \left(F_{DG,DES} + \frac{E_{grid,DES}}{\eta_{grid}} \right)}{\frac{1}{\eta_{grid}} \cdot (E_{d,CES} + E_{sell,DES})} dt \tag{8}$$

4. Case description

4.1. Energy demands

A building cluster including twelve buildings in the Hong Kong Polytechnic University (PolyU) are concerned as end users. Those buildings have different functions, such as the library, lecture rooms, office and laboratories. The total floor area of those buildings is 252,901 m^2. The in-building electricity demand, which includes the consumption of lighting/equipment, and the HVAC auxiliary equipment (fans, pumps and cooling tower), is collected by CLP (a local power company) meters. The cooling demand of each building is recorded by the integrated BMS (building management systems), a building automation monitor system. The profile of hourly electricity demand and cooling demand of the whole campus in 2015 are shown in Fig.3.

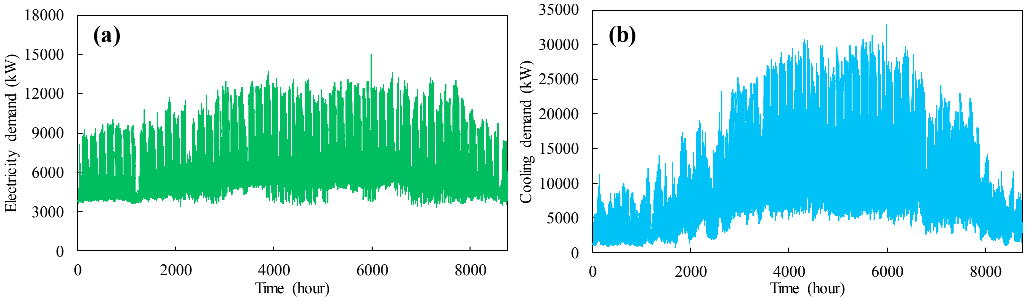

Figure 3. (a) Total electricity demand of the campus; (b) Total cooling demand of the campus

Table 1. Information of chillers in each building

Building	CP_{ec} (kW)	N_{ec}	COP	Building	CP_{ec} (kW)	N_{ec}	COP
JCA	445	2	5.18	Phase 3B	1110	3	5.24
JCIT	890	3	5.22	Phase 4	1138	3	5.25
PCD	650	3	5.20	Phase 5	730	2	5.20
Phase 1_2	1110	5	5.24	Phase 6	1140	4	5.25
Phase 2AB	845	4	5.22	Phase 7	990	4	5.23
Phase 3A	680	3	5.20	Phase 8	1670	4	5.31

Table 2. Energy prices adopted in this study

Energy	Electricity	Natural gas	Feed-in tariff	*PS*
Price (USD/kWh)	0.192	0.057	0.163	0.046

Table 3. Equipment capacities and efficiency of the DES

	DGs	Absorption chillers	Electric chillers
Capacity (kW)	5900×2	2054×6	3980×6
Rated efficiency	48.28 %	1.20	5.61

4.2. Configuration of CES and DES

In the CES, the electricity demand is imported from the utility grid, and the cooling demand is supplied by water-cooled centrifugal chillers. The number and capacities of chillers in each building is determined by the campus planning as presented in Table 1.

In the DES, the CHW networks are organized in star shaped networks. Three secondary loops, each connects four buildings, deliver chilled water from the energy station to end users. The designed supply and return temperatures of chilled water are 7 ℃/12 ℃. With the cooling demand of each user and building location, the size, diameter and length, of each pipe can be determined. Ten primary pumps (each for one chiller) and sixteen secondary pumps are selected in this system. The pump head can be determined based on the flow volume and the resistance of CHW networks. The energy prices which are adopted in this study are shown in Table 2.

5. Results and analysis

The capacities of energy supply equipment in the DES are determined by the cost-optimal design method as shown in Table 3. Fig. 4 shows the hourly electricity demand of the CES (a) and the DES (b) in a typical summer week. It can be seen that the electricity demand of chillers is reduced, especially in the nighttime. It is because absorption chillers satisfy part of cooling requirement in the DES, and the cooling provided by electric chillers as well as the consumption of those chillers is reduced. Additional electricity is required by pumps, however, this part of consumption is not significant. The dash line presents the electricity load of the grid. The DES imports less electricity from the grid due to the operation of DGs. The using of DES reduces the grid load significantly, for example, the peak grid load in the selected week is decreased from 18,671 kW to 5,092 kW. In the nighttime or the day when electricity demand is relative low, DGs satisfy the demand and no electricity is purchased from the grid. The reduction of the grid load results in the significant reduction of the grid pressure in electricity supply. With the using of the DES, the reliability of electricity supply is improved.

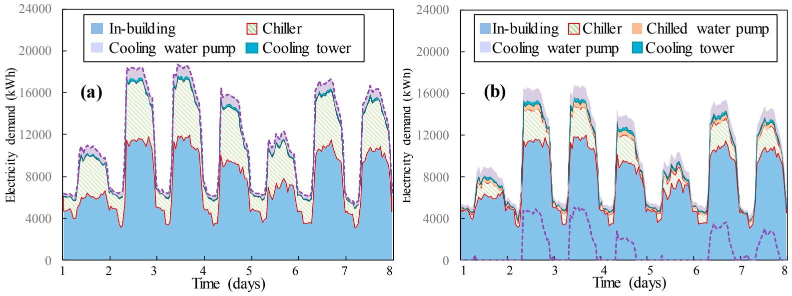

Figure 4. (a) Electricity demand of the CES in a typical summer week; (b) Electricity demand of the DES in a typical summer week

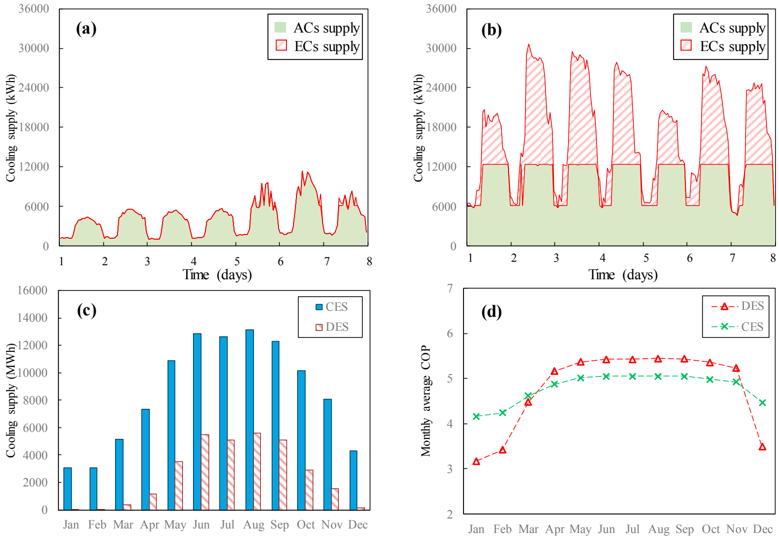

Figure 5. (a) Cooling supply of the DES in a typical winter week; (b) Cooling supply of the DES in a typical summer week; (c) Monthly cooling supply of electric chillers in the CES and the DES; (d) Monthly average COP of electric chillers in the CES and the DES

Fig. 5(a) and (b) presents the cooling supply of the DES in a typical winter week and a typical summer week, respectively. It can be seen that most cooling is supplied by ACs in the winter week, in which the cooling demand is relative low. In the summer, ACs cannot satisfy the high cooling demand and ECs operate to supplement the cooling demand. The outputs and performance of electric chillers of these two energy systems are compared and shown in Fig. 5(c) and (d). Due to the operation of absorption chillers, the monthly cooling supply of electric chillers in the DES is much less than the CES. The comparison of monthly average COP of electric chillers indicates that in the most time of the year (form April to November), chillers in the DES operate with higher COP than the CES. It is because the chillers in the DES have higher capacities and rated COP. However, the average COP of chillers in the DES is lower than the CES in January, February and December. It is because the output of chillers is low so that chillers operate in part load with lower practical COP. The annual average COP of electric chiller in the DES is 5.36, which is obviously higher than the CES, 4.91.

The consumption of primary energy and the cost of those two energy systems are compared. Primary energy saving (PES), which is the ratio of saved energy to the consumed energy, indicates the energy benefits of the DES. Fig. 6(a) shows that the DES consumes less primary energy than the CES in every month. The monthly PES various from 7.36% to 10.32%. Annually, 9.58% of primary energy can be saved. Fig. 6(b) shows the composition of the capital cost and the operation cost of each energy system. With the extra networks and DGs, the capital cost of the DES is 20,732×10^3 USD, which is more than three times of the CES, 7,218×10^3 USD. However, the operation cost of the energy system is much lower due to the high efficiency of energy utilization. For the CES, the annual operation cost is 16,561×10^3 USD while the annual operation cost of the DES is 9,245×10^3 USD. The additional capital cost of the DES can be recovered in 1.93 years, then the system can benefit for less operation cost.

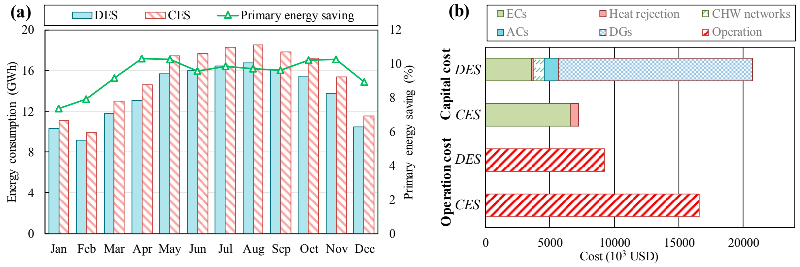

Figure 6. (a) Monthly primary energy saving of the DES; (b) Details of the cost of the DES and CES

6. Conclusions

A distributed energy system in a Hong Kong campus is designed and the performance is investigated. A cost-optimal design method is adopted to determine the equipment capacities of the DES. Test results denote that the DES can achieve better performance than the CES in term of energy supply and economic. Conclusions can be drawn as follows.

1) In the DES, DGs generate electricity so that less power is imported from the grid. The peak load of the grid is decreased significantly (from 18,671 kW to 5,092 kW in a selected summer week). Thus, the safety and reliability of the grid can be enhanced.
2) The performance of chillers in the DES is better than the CES. Electric chillers with larger capacities and higher efficiency are adopted in the DES. Those chillers operate with higher COP in most period of the year except for few months.
3) The overall energy efficiency of is higher than the CES. 9.58% of the primary energy can be saved annually when the DES replaces the CES. The DES has a better economic performance than the CES. When the DES is adopted, the operation cost is reduced. The payback period of this system is 1.93 year.

References

[1] K. Alanne and A. Saari, Distributed energy generation and sustainable development, *Renewable and Sustainable Energy Reviews*, 2006; 10: 539-558.
[2] L. Li, H. Mu, N. Li, and M. Li, Economic and environmental optimization for distributed energy resource systems coupled with district energy networks, *Energy*, 2016; 109: 947-960.
[3] H. Cho, A. D. Smith, and P. Mago, Combined cooling, heating and power: A review of performance improvement and optimization, *Applied Energy*, 2014; 136: 168-185.
[4] W. Gang, S. Wang, D. Gao, and F. Xiao, District cooling systems: Technology integration, system optimization, challenges and opportunities for applications. *Renewable and Sustainable Energy Reviews*. 2016; 53: 253-264.
[5] CLP Hong Kong. CLP Information Kit. Available: https://www.clp.com.hk/en/about-clp-site/corporate-information-site/
[6] GE Jenbacher gas engine. Available: https://powergen.gepower.com/products/reciprocating-engines.html
[7] J. Kang, S. Wang, W. Gang, Performance of distributed energy systems in buildings in cooling dominated regions and the impacts of energy policies, *Applied Thermal Engineering*, 2017; 127: 281-291.
[8] Hu M et al. Investigation of demand response potentials of residential air conditioners in smart grids using grey-box room thermal model. *Appllied Energy* (2017); http://dx.doi.org/10.1016/j.apenergy.2017.05.099.